

Structural approach to safety analysis of NPP on base of coolant oscillations modeling and forecasting of the NPP Fundamental Equipment Reliability.

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1. ABSTRACT

The new approach to the assessment of long-term forecast for large-sized NPP elements' reliability with the using the method of the invariant mathematical classification is proposed. The general idea is in separation of the set of similar objects - A on classes which are invariant in time. This is achieved by determination of appropriate transformation of original parametrical space of objects. As one of component of parametrical space is considered vibrations and coolant pressure oscillations.

2. THE FORECASTING OF POWER PLANT LARGE-SIZED EQUIPMENT RELIABILITY.

From the analysis of physical principles of PV reliability follows that the parameters defining its reliability influence enough strong each other. In the standard analysis it can be taken into account by introduction of correlation between parameters and use of appropriate dispersion matrixes at calculation of the forecasting. However the reliability of PV is influenced by enough large set of parameters, thus for constructing dispersion matrix which is taking into account correlation between many parameters the available information is obviously poor. Therefore it is reasonably to consider the alternate nonconventional approach, which can to take into account existing problems. Besides, such approach is important, which can allow to conduct monitoring of object in service and taking into consideration various influences on object to correct its reliability long-term forecast. In this paper we are considering as the object the pressure vessel (PV) of reactor but this approach can be used as well to other similar large size objects of NPP as steam generator, transformer and so on.

For the analysis of PV reliability we assume that:

- 1) A complex interaction between parameters of object reliability takes place.
- 2) The stochastic influence on the parameters exists. This gives the random distribution of the parameters.
- 3) The uncertainties of the models exist. This also gives random variation of the parameters.
- 4) Set of existig PV is enogh small from st statistical point of view.

Let suppose we have a vector of reliability parameters of the some object X with dimension n . Its components have the probability distribution $f_i(x_i)$, $i=1,...,n$. Therefore using methods of reliability analysis we can find the failure probability of the object. We have the reactor vessel - A_0 . If the necessary data is available then one can calculate the failure probability at point of time T_1 . But we want to know the object conditions after time ΔT at $T_2 = T_1 + \Delta T$.

Let we have the PV of the certain type - object A_0 . It is described at the moment of time T_1 by the vector of characteristics X_{10} . We also have the set A of objects with the similar structure $\{A_i, i=1,...,N\}$. N is the number of the objects that have the duration of work $T_1 \geq T_2$ (in this set the reactors' vessels of the similar type are included, but of various modifications). We are interesting in the parameters vector X_{20} of the object A_0 in point of time $T_2 = T_1 + \Delta T$.

We consider the case of steady-state use of the NPP. Therefore, all functions have not breaks and are enough smooth. One can try to define the vector X_{20} from the set A . We will use the methods of mathematical classification. By direct determination of the forecasting parameters from all item of set A we can receive the enough large uncertainties in values and, therefore, the large uncertainty for the value of reliability forecast. It is necessary to find out in set A the objects that are most similar to the analyzing PV A_0 , and using this basis we can estimate the interesting us parameters of forecast. The problem of the mathematical classification consists in the separation of set A on l number of classes. For this purpose it is possible to use various methods of classification (for example on basis of neural network). We used our own approach on base hierarchical classification with which it is possible to find R_{op} - the optimal classification of the objects.

Now we can consider the process of generation of the parameters' space, which describe our objects - PV. First, we will take into account only parameters, which directly describe the PV reliability. As the basis for the reliability analysis the methods of the fracture mechanics by means of the theory of the linear elastic fracture mechanics are used (without any problem other mechanical approaches can be considered). Therefore the reliability of the PV should be defined as relationship between K_I - stress intensity factor and K_{IC} - crack initiation toughness. If the classification is performed only in such space, then the variants of distribution the objects on classes at points of time T_1 and T_2 can be different (the Fig.1. presents the illustration the simplest case for two-dimensional variants of parameters' space).

The reason of such behavior (for example for moment of time T_1) can be explained as follows:

$$\begin{aligned}
 X_i[x_{i1}, ..., x_{in}] &\in R_l; x_{ik} = f(X_i, Y_i, T) \\
 X_j[x_{j1}, ..., x_{jn}] &\in R_l; R_{op} \in X; R'_{op} \in Y \\
 Y_i[y_{i1}, ..., y_{in}] &\in R'_l; R_l \in R_{op}; R'_l \in R'_{op} \\
 Y_j[y_{j1}, ..., y_{jn}] &\notin R'_l; X_i, X_j \in X; Y_i, Y_j \in Y
 \end{aligned} \tag{1}$$

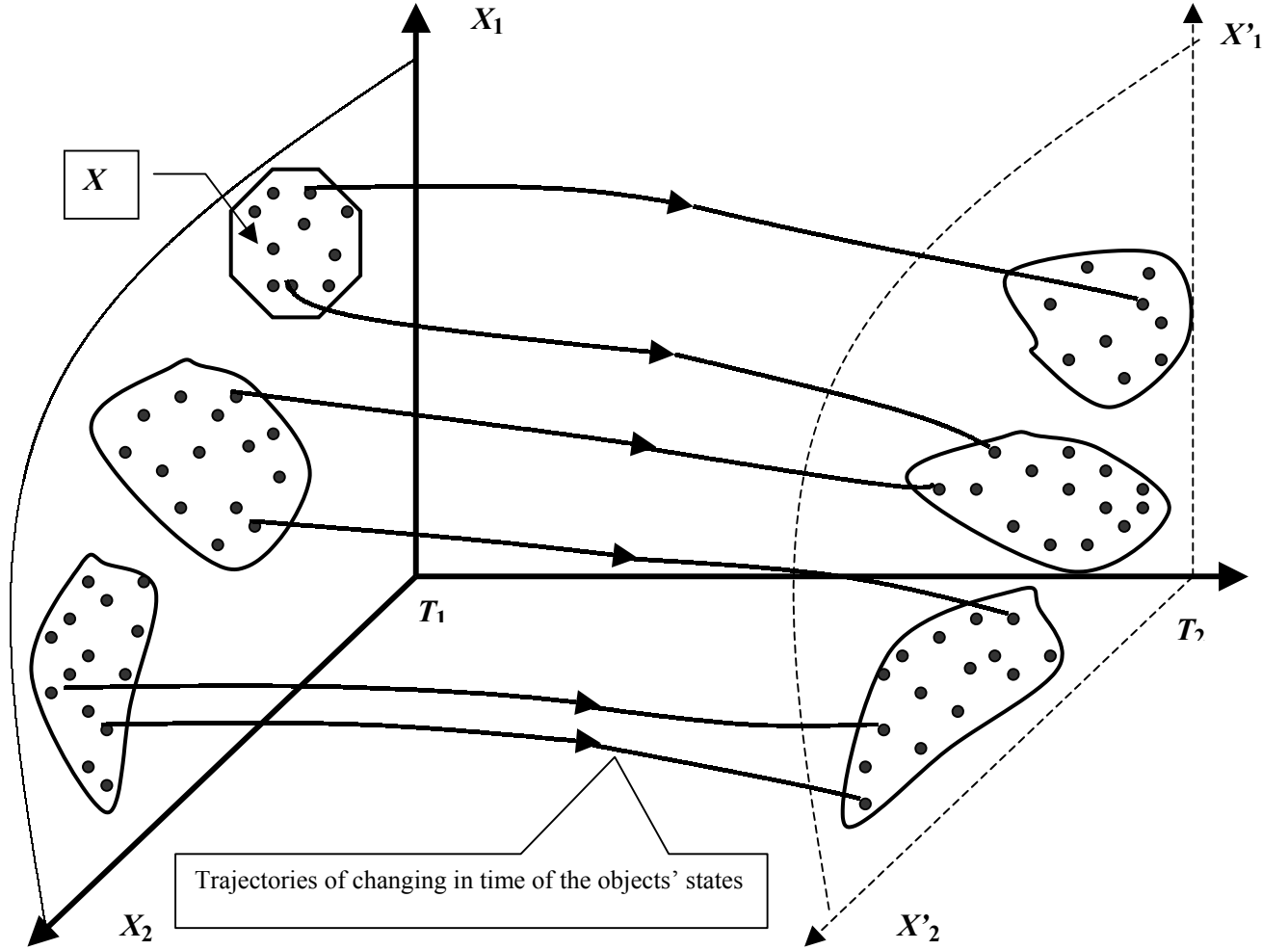


Fig. 1. Separation of objects by classes at moments of time T_1 and T_2 for the simplest case of two-dimensional parameters' space (X'_1 and X'_2 – coordinates of objects at moment of time T_2)

Here R_l is a class; X_i and Y_i are same parametrical vectors of object A_i in different moment of time in parametrical subspace X and Y accordingly. To take into account (1) we change the description of the object from space X to space $Z = X * V$. The subspace V is designed on principle the complete description of every parameter from space X . Therefore the situation (1) will be eliminated.

However some difference between the classifications at the moments of time T_1 and T_2 can remain by the some reasons. This is possible because of the existence of the stochastic influences both at the moment T_1 and moment T_2 (in general on interval ΔT) which can touch of all objects of the set A . Thus, we have to take into account it on the interval of time ΔT for forecasting of the PV A_0 parameters. We can achieve this on the base of some transformation of space Z with functions f_1 and f_2 for moments of time T_1 and T_2 accordingly: $T_1: \{Z' = f_1(Z)\}$; $T_2: \{Z'' = f_2(Z)\}$. As a result the set A classification will be invariant relatively the times T_1 and T_2 :

$$\forall A_i, A_j : T_1 : Z'_i \in R_l \quad T_2 : Z''_i \in R_l; i, j = 1, \dots, N \quad (2)$$

$$Z'_j \in R_l \quad Z''_j \in R_l; R_l \in R_{op(P)}$$

If the expression (2) is valid, it can restrict the possibility of the stochastic influence on the objects at the given time interval ΔT in boundaries of appropriate classes. On the base of Shannon's principle one can say, that having the general rule of invariant distribution of the objects on the classes at the time moments T_1 and T_2 for the set A we can suppose that we have equivalent general rule for set $A' = A \cup A_0$. Let's at the time T_E k objects is contained in the class R_{El} ($l=1, \dots, R_{opE}$). In moment T_H this class decomposes into points, which are distributed among m_{rHl} classes:

$$\{n_j | j=1, \dots, m_{rHl} | k = \bigcup_{j=1}^{m_{rHl}} n_j | A_{ij}[i=1, \dots, n_j] \in R_{Hj}\}, (E \neq H | E, H = 1, 2). \quad \text{The ratio } s_{Hjl} = \frac{n_j}{k}$$

characterizes the hit probability of objects from considering class R_{El} at the class R_{Hl} at the time T_H , which will be equal to 1 in

the case of classification, which is invariant from time. The function: $S_{TE} = \frac{\sum_{l=1}^{R_{opE}} \prod_{j=1}^{m_{rHl}} (1 - s_{Hjl})}{R_{opE} (1 - 1/R_{opE})^{R_{opH}}}$ will tend to 0 by

the approach of the invariance. The summation S_{TE} on T_1 and T_2 takes into account the influence at both moments of time.

$$W = S_{T1} + S_{T2} \quad (3)$$

The analysis of W and S_{TE} allows to conclude, that in the considering area and by given conditions a minimum of the expression (3) will take place. Therefore, we have to find the transformations f_1 and f_2 for which the minimum of (3) equal to 0 takes place and as result we will get the validity of the condition (2). Thus, we have two sets of classes sets: R'_{opE} for the time T_1 , and R'_{opH} for the time T_2 , which are equivalent by distribution of the objects. For the object A_0 by the same rules as for the set A objects we form vector Z_0 , which describes it and belongs to the space Z . Using transformation f_1 the vector Z_0 is found for the space Z' : $Z'_0 = f_1(Z_0)$. Further, one can find the class in R'_{opE} , which contains Z'_0 . This belonging, say for R_{El} , and because of the invariance that is found above in time interval ΔT it allows to predict the belonging of the vector of the characteristic of the object A_0 to the class R_{Hl} at the time T_2 and for the space Z'' . Using the deviations of the vectors of the set A which belong to R_{Hl} , one can find the appropriate parametrical vector of object A_0 . After that, using the inverse transformation technique from space Z'' , one can find the value of the vector, which belongs to the space Z at time T_2 and consequently, the vector X_{20} . After that, using well-known probability relationships, one can obtain the forecast of the PV reliability P_P at the time T_2 .

By this approach the series of calculations were conducted, which shows that forecasting on base of developed approach is more precise in comparison with standard methods.

Above possibility of forecasting of reliability PV in some moment of a time T_2 was considered. Thus it meant, that T_2 is enough large value in comparison with in term of object operation. Thus, the given forecast of reliability can be referred to the long-term forecast. In particular, it needs to be conducted on a stage of designing for choice of optimum design decisions. But every long-term forecast always has some errors. To decrease it the method of monitoring and correction of original forecast on base of the data of object's service are offered.

An example formulation of the method of the prognosis of the PV parameters for the PWR is presented below. Here it is not discussed the logic of choice of the physical assumptions. The parameters Φ (neutron fluence), Cu - copper content, Ni - nickel content are included additionally together with K_{IC} in the space Z . The parameter K_I is characterized through features of crack growth through the Paris's equation parameters $da/dN_C = C (\Delta K_I)^l$: C and l , the number of the cycles N_C . On the basis of these parameters at the time T_1 , it can calculate the failure probability for analyzing PV. Certainly, the set of the parameters can be extended, but for simplicity it is assumed, that this information is enough for description of our parameters' space. Hence, constructing on the base of these parameters the parameters' space, which describes the PV, we have carried out the above criteria by account the interaction between parameters. The set A is formed by the PWR reactors' type. We assume that set of considering reactor vessels is enough homogeneous by technology of manufacture and installation. This assumption provides the smooth type characteristics. For 52 reactor vessels the calculations are simulated (on the base of the data from the literature sources). The moments of time are as follows: $T_1=10$ years, $T_2=30$ years. For the set A the influences are simulated using the literature data. It was simulated conditions of LOCA type accident. For the Cu , Ni , l , N_C is used as normal distribution, for the parameter C - Log-Normal distribution, for the K_{IC} - Weibull's distribution. According classification the set A consisting of 52 PV is shared at the moments of time T_1 and T_2 on 6 classes. For some PV a shift from one class to another is observed depending on the moment of time. To remove this shift the transformations are used with principles on the base of (3) for the spaces, which contains the set A at the moments of time T_1 and T_2 . This allows to go to invariant by the time classification (2) and to restrict the stochastic impact on the objects for period of time $\Delta T=20$ years in boundaries of the classes chosen.

Let at the moment of time T_1 the analyzing object has the parameters as follows: $K_{IC}=94 \text{ MPa}\cdot\text{m}^{1/2}$, $\Phi = 6.5 \cdot 10^{18} \text{ n/sm}^2$, $Cu=0.12\%$, $Ni=0.6\%$, $C=1.1 \cdot 10^{-9}$, $l=2.5$, $N_C=2 \cdot 10^6$ cycles. Using the transformations proposed we include such object at time T_1 in the 4th class. Because of the invariance for classification by the time then at moment of time T_2 the considering object also belongs to the 4th class. After the inverse transformation of the intervals of the parameters for the moment of prognosis time T_2 one can assume, that the considering object will have at the moment of prognosis time characteristics, which are caused by the interval of the parameters values belonging to the class 4: $K_{IC}=66 - 81 \text{ Mpa}\cdot\text{m}^{1/2}$; $C=9.28 \cdot 10^{-10} - 1.4 \cdot 10^{-9}$; $l=2.4 - 2.9$; $N_C=6.3 \cdot 10^6 - 7.8 \cdot 10^6$ cycles. For the more accurate prediction of the parameters on the given set of the objects from this class one can use the other methods, for example, regression methods. In this case the model will have fewer uncertainties in comparison with the case with modeling on the all set A . On the basis the well-known probabilistic expressions it can obtain the appropriate assessment of the reliability at the moment of time T_2 . Some example of using the developed approach to forecasting of the PV reliability and correction of the PV parameters during work time shows on fig. 2.

The 1-6 curves show the dependence of conditional probability of PVs failure by pressurized thermal shock belonging to 1-6 classes. Number 7 shows trend of conditional probability of failure for assessment on base whole set A with use standard methods. Comparison curve 7 with curve for class 4 shows that forecast on base of developed approach gives more precise result.

By appropriate funding the following interesting further development of the approach can be based on using in addition methods of artificial intelligence. Two main directions are considered. One is in increasing correctness of invariant classification and monitoring [1] with using of clusterization methods on the basis of neural networks. Another is based on

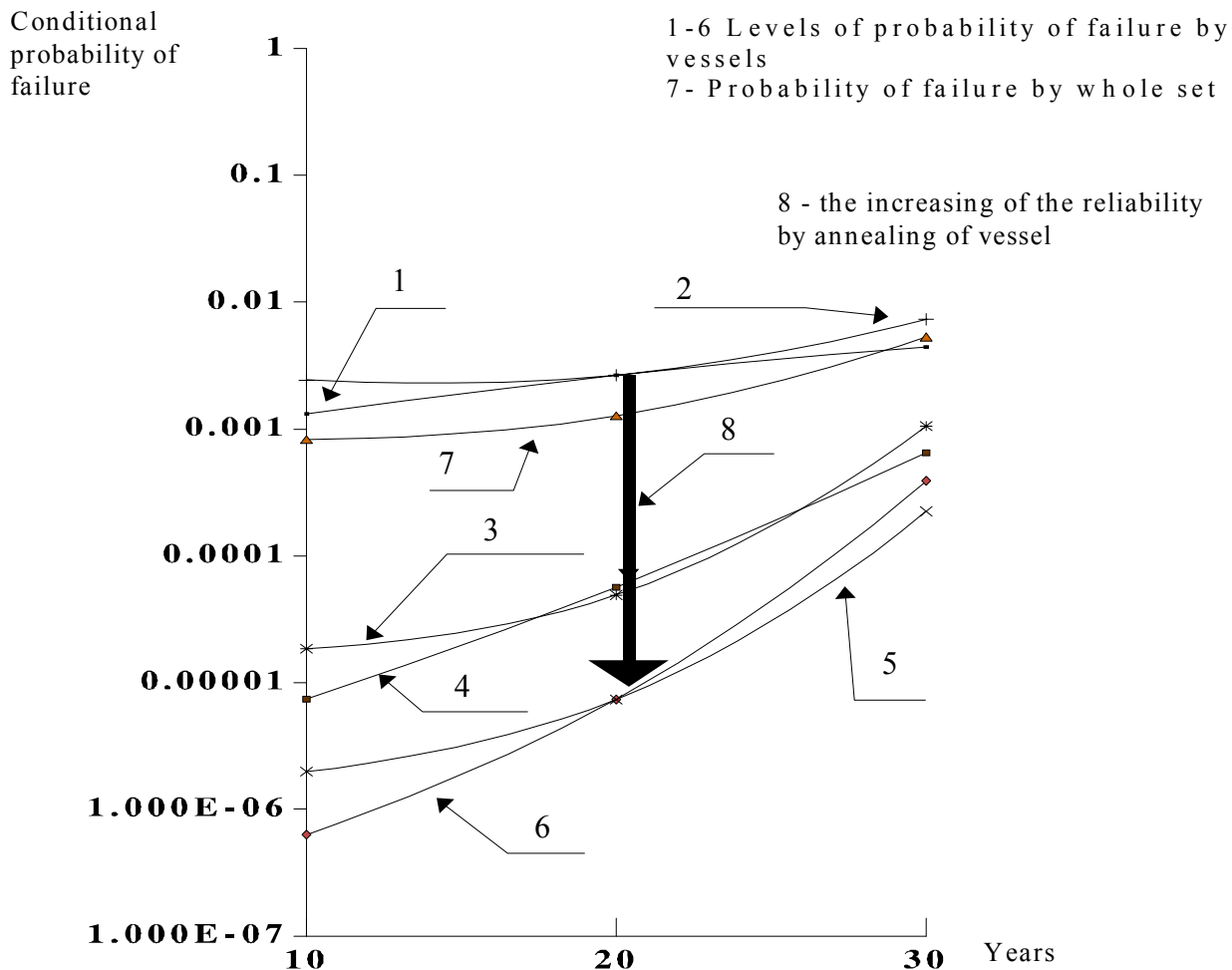


Fig. 2 Changing of probability of failure by classes

using of neural networks for correction of NPP state from the point of view of their reliability by optimization of their characteristics on the basis of simulation of NPP dynamic behavior as whole complex object with using of modern best estimate codes RELAP5 type. Further it will be considered parametrical oscillation which occurs in NPP thermal-hydraulic system and which must be taking into account by construction above described of NPP equipment parametrical space.

3. THE PHENOMENA OF PARAMETRICAL OSCILLATION IN NPP THERMAL-HYDRAULIC SYSTEM

The WCOBRA/TRAC, CATHARE2, RELAP5 and APROS codes are the estimate thermal hydraulic codes for the evaluation of large and small break loss of coolant accidents (LOCA). The relatively good agreement experimental data with the calculations have been presented. There also was shown some big mistakes in predicting distribution of flow when two phase are present. Model of parametrical oscillations (P.O.) worked out [2] gives explanation for flow oscillations and indicates that the phenomenon of P.O. appears under certain combination of thermal-hydraulic parameters and structure of heat-removal system. CATHARE and RELAP5 codes have been used to help analyse the GDE-05 experiment from the first passive safety injection experiment series [3]. The purpose of the CATHARE and RELAP5 analyses was to help understand the phenomena observed in the experiment. The main phenomena of interest were the natural circulation flow of water through the passive safety injection system lines and the condensation phenomena in the CMT(Core Make-Up Tank).

The SPES-2 tests were performed as part of the ALWR program sponsored by the U.S. Department of Energy (DOE) and the Electric Power Research Institute (EPRI). Westinghouse, performed the SPES-2 tests to obtain data on the integrated behavior and performance of the AP600 passive systems to support validation of the computer codes to perform the licensing safety analyses for the AP600. The SPES-2 test matrix includes eight different LOCA simulations with a wide selection of sizes and location in order to observe the integrated operation of the passive system over a wide range of conditions. Moreover three Steam Generator Tube Ruptures (SGTR) and one Main Steam Line Break (MSLB) have been performed.

The results of WCOBRA/TRAC simulation had been compared with the test results [4]. Due to the rapid loss of pressure down to saturation pressure for the core and upper plenum, core boiling initiates and upper plenum flashes while the fluid level decreases down to the hot leg elevation. Comparison between prediction and data is presented. Comparison show that, in the period from 300 to 2500 s after the start of emergency cooling, the amplitude of oscillations of the mass flow rate of the coolant can become very large. The results of calculations using the WCOBRA/TRAC code do not give a detailed description of the dynamics of the mass flow rate in this time interval.

The mathematical model worked out for parametrical oscillations of the coolant due to a periodic change in the elasticity of the latter enables us to determine the boundary (critical) value of the modulation of this parameter. This model for

revealing in more detail the dynamic processes in the coolant of the passive protection systems for the core was proved to be applicable.

The new dimensionless product – parametrical similarity criterion of steam generating ducts (PSCSD) is created. The critical value of the modulation index χ_{cr} corresponds to the boundary conditions under which PO arises.

$$\chi_{cr} = \frac{v_m}{\alpha_m} \left(\frac{\rho_m}{\rho_w} \right)^{1/2} \left(\frac{\Delta h_{out}}{\Delta h_{inl}} \right)^{1/2} \left(\xi_{fr} \frac{1}{d} + \sum \xi_{loc} \right)$$

Eigen frequencies of coolant oscillations may coincide with the eigen frequencies of oscillations of the equipment or of its individual items (it amounts to resonant interaction between the equipment and the coolant). In these cases, the amplitude of oscillations of the coolant, as well as of the equipment itself, increases. The probability that such conditions will arise becomes greater for changes in the way the items are mounted for normal operation, and also during transients.

Even short-term resonant interaction between the coolant and the equipment (during transients, for example) can greatly reduce the service life of the equipment and/or the parts of the constructions; in certain cases, it may be the cause of an accident.

4.CONCLUSION

The offered technique of the reliability forecast is applicable on all stages of life of any large-sized equipment NPP: at the stage of designing and at manufacturing; at installation and under operating conditions. The unique kind of equipment is not an obstacle for use of a technique, i.e. the offered approach enables real management of reliability of any equipment.

The worked out model describes mathematically the mechanism for exciting parametrical oscillations when the compressibility of the steam-water mixture varies periodically. The frequency of these oscillations depends not only on the parameters of the thermal-hydraulic processes, but also on the geometrical dimensions of the heat-removal system and the stage of the process of cooling down the core. An analysis of the model indicates that the phenomenon of parametrical oscillations appears under certain combinations of the above-mentioned factors. A detailed list of these factors includes the intensity of steam formation, the structure of the two-phase flow, the configuration and dimensions of the elements that form the passive safety injection systems (PSIS).

Optimizing of PSIS is possible on base of developed criterion, which can allow to control of oscillation and even prevent it. Another possibility exists in joint use of developed criterion with modern best estimate codes (RELAP etc.) and presented below approach of NPP safety comprehensive analysis. Obviously, that for development of practical recommendations it is necessary full-scale funding of research and development on presented directions.

5.PERSPECTIVES

Today such branches of science as best estimate codes (RELAP5, ATHLET, TRAC etc.), methods of optimization including technologies of an artificial intelligence have reached high level of development. Separately they are widely used in a justification of reliability and safety of NPP.

In the current technology the research of possible accident or transient regime on NPP is reduced to a numerical modeling of restricted number of variants by best estimate codes. Expert analyses of the obtained data are based upon gained experience of NPP operation and upon calculated data. Next, the guidelines for minimization of accident negative consequences are elaborated and confirmed by calculations.

By virtue of natural limits of knowledge and experience of the person or group of the people such approach does not eliminate a possibility of a qualitative error, i.e. skip of a situation, qualitatively diverse, than known from preceding experience. Let's give as an example a not apparent situation, when more dangerous from the point of view of minimization of Peak Cladding Temperature is the small LOCA, instead of large LOCA, or situation, when depressurization of steam generator after accident can relief course of accident.

The usage of an expert analysis does not change main point of problem. In conditions, when the task is not strictly formalized, experience of the separate person or professional group becomes as criterion, which one is fastened in the form of the heuristic rules set, stereotypes. The stereotypes of thinking seldom and difficulty yield to revising. Even if the carriers of stereotypes are the experts of high qualification.

Notwithstanding the achieved high level of codes development, the successes in modern methods of optimization allow to make a pitch to qualitatively diverse level of the analysis of an assigned situation.

The high level of development of modern best estimate codes (it is the conventional fact) means a high level of adequacy of the models simulating real Nuclear Power Plants. In other words, in the available models of the NPP suitable information about possible accidents and processes included. The amount of the information is restricted only by degree of model adequacy.

For deriving this information it is proposed to combine the capabilities of best estimate codes with different modern technologies. For this purpose it would be expedient to create the software, which one could:

- 1 To use the best estimate code as an information generator about NPP performance (i.e. capability to calculate any parameter under given conditions);
- 2 To produce necessary control of the best estimate code calculation (i.e. control of deriving of the information) getting the possibility of evaluating the obtained information. This makes possible the feedback with control procedure of the calculation on the basis of modern technologies of optimization.

Actually it would mean creation of effective toolkit for the analysis of NPP transient and accident regimes. Some methods of the obtained information processing (from the elementary methods of multivariate optimization up to technologies of an artificial intelligence) would allow to conduct from multivariate optimization of transient up to an automatic scan of potentially accidents.

The benefits of developing such software are quite significant because the software could be adapted and used for a variety of NPP safety codes such as RELAP5, ATHLET, MELCOR, TRAC, GOTHIC, etc.

The authors propose the new approach to research of NPP safety with use of the modern best estimate codes and the first version of the software realization is represented. This approach can be considered including as a possibility of optimization of a state of the fundamental equipment of NPP, that will allow to control its reliability.

The approach uses ability of modern codes to represent practically any preset situation on NPP and it is realized as the software - intellectual agent, under monitoring and control of which code is working. The integral code at this approach is an information generator, which one is researched by the software - agent.

The researching is carried out as the process of optimization at optimized parameters, which are given by user and criteria of optimization.

The software - agent analyzes the obtained information and adjusts operation of the code, in order to receive the information interesting for us. It can be:

- Values of equipment operation parameters, potentially dangerous from the point of view of accidents origin or unusual situations;
- Values of equipment operation parameters, which are appropriating to the best or worst course of accident and transient;
- Searching of parameters, which are best fitting to available data (restoring of a course of the process on data “ of a black box ”).

In more detail given approach is represented in [5].

The version of the software under operating system Linux Slackware (UNIX clone) for the Relap5 mod.3.2 best estimate code is realized, its functional testing is carried on, the first interesting results are obtained. The software can be adapted to other best estimate codes. Further development by appropriate funding can be considered on base of using of modern technologies such as:

- Evolution algorithms;
- Parallel calculations;
- Neural-statistical approach.

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